Electrical properties of Portland cement, with the addition of polypropylene fibres – regarding durability

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Introduction

It has been estimated that if polypropylene fibres are universally adopted as a concrete additive, the reduction in maintenance and remedial work to reinforced concrete structures, currently estimated at UK, £550 million pounds per annum (National Physical Laboratory, 2000), will be significant. In addition, "with a world production of around 5 billion tonnes of concrete a year – nearly one tonne per person per year – concrete is probably the most common material in modern construction" (Kernan, 2003). If this concrete can be produced with lower life cycle costs due to enhanced durability, this will have a significantly reduced environmental impact on our world.

The addition of polypropylene fibres to concrete may significantly and beneficially affect the mobility of ions in the concrete matrix by causing physical changes in the microstructure. The fibres themselves are electrical insulators and hence, their presence will cause a volumetric increase in the resistivity of the concrete. In addition their presence may also cause a reduction in thermal micro cracking and hence a decrease in the ionic permeability. Impermeable concrete will restrict the access of surface contamination to the reinforcing steel, at the initiation stage of corrosion attack. Thus, the use of appropriate fibres in concrete may have an increase in the durability of a reinforced concrete structure; resulting in lower life cycle costs. This potential trend for enhanced durability can be added to the other benefits of using monofilament polypropylene fibre in concrete, such as low absorption (Richardson, 2003c), freeze/thaw resistance (Richardson, 2003d), fire resistance (Kitchen, 2001) and micro reinforcement.

The purpose of this series of electrical conductivity tests, was to compare the resistivity of cement grout with polypropylene fibre additions at a commercially accepted concentration of 0.91 kg/m^3 with a control sample of pure cement grout. The pore structure of hydrated cement in mortar and concrete is quite different from that of neat cement paste (Bentz and Garboczi, 1995). The porous transition zones formed at the aggregate paste interface affect the pore size distribution. However, Bentz and Garboczi found that, aggregate additions have a minimal effect on the final cement product with regard to the measured pore radius and subsequent permeability. What is much more significant is the degree of hydration of the cement with regard to pore size formation and also the introduction of

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sand, which increased the transport coefficients. Both Abo El-Enein *et al.* (1995) and Bentz and Garboczi (1995) showed that neat cement, mortar and concrete had variable electrical conductivities depending upon the water/cement ratio (w/c), whereby there is a direct relationship between w/c and conductivity. The testing described in this paper uses a constant w/c to ensure that the results can be compared objectively.

Earlier studies have shown that the rate of diffusion of chlorides through concrete is increased by the application of an electrical field (Nilsson and Tang, 1995). This would indicate that, a material capable of high electrical conductivity is also capable of a higher rate of ion flow as defined by Lu (1997). This view is further corroborated, "The electrical resistivity of the concrete affects the ionic flow...a higher concrete resistivity decreases the current flow .... The electrical resistivity of concrete depends upon the capillary pore size, pore system complexity and moisture content. Chlorides have little direct effect on resistivity as the hydroxyl ions from the cement dissolved in pore water out number the few chloride ions" (Broomfield and Millard, 2002, p. 37). This statement as to the effect of chlorides in water is not consistent with work of Castellote *et al.* (2001); they imply that chloride concentration is directly proportional to conductivity measured in mS/cm. This implies that resistivity results would depend upon chloride concentration in the pore structure rather than the effect of fibres, however, for the sake of the current tests, the mineral content of water used will be ignored due to the fact that all of the samples are being subjected to identical testing regime. However, when designing for durability the type of water the concrete will encounter may affect the migration and diffusion, depending upon, for example, the "hardness" or exposure to sea water.

Test procedure

For each additive to be tested, four OPC and water grout sections were manufacturered with w/c of 0.5. Their sizes were 100 mm × 100 mm approximately 50 mm thick. The sections were a plain control sample, and samples with the following fibre additions: 19 mm monofilament polypropylene fibres, 38 mm fibrillated fibres, and 6.5 mm monofilament polypropylene fibres.
The reason behind using 50 mm thick samples was outlined by Chrisp *et al.* (2002, p. 426), who stated, "the response at 50 mm remains relatively unaffected by wetting and drying action at the surface and reflects hydration effects". This characteristic would allow measurements to be taken at progressive degrees of absorption, analysing resistivity at various saturation states due to absorption through the covercrete.

After casting and the initial set taking place, the moulds were removed and the samples were placed in a curing tank for 28 days. Prior to testing, the samples were wiped dry with a cloth, then the samples were weighed and the weights recorded, after which tests were carried out to determine the resistance value for each saturated section.
It was noted that no cracking was visible upon the grout sections. The voltage used to test the concrete was kept low in order not to produce heat in the sample, which would have provided spurious results.

Following the original resistivity test the samples were placed in a drying oven for 24 h, where the temperature did not exceed 120°C, to ensure that no damage occurred to the fibres due to excessive heat. The saturated moisture content (Table I) per sample was calculated and divided by five to establish a 20 per cent moisture content, by weight, which relates to values between 33 and 36 per cent by volume for full saturation. Contact plates were clamped to either side of the specimen, the apparatus was calibrated and the resistivity was measured when sample was dry. Water was measured out for 20 per cent of the total water absorbed per sample and stood in a tray to reabsorb the liquid for 30 min, covering the sample and tray with an impervious material (low density polyethylene film) to prevent evaporation.
The 30 min absorption time period was used to reflect absorption in BS 1881:Part 122: 1983 and this proved to be sufficient to absorb water, whilst ensuring reasonable dispersion within the sample, as the section was 50 mm thick and the BS cores used to determine water absorption are 75 mm

Table I Physical properties of grout samples

Cube type	Cube reference	Wet weight (g)	Cross sectional area (mm)	Thickness (mm)
Plain	1	902.96	100.5 × 101	44
Plain	2	881.06	99 × 100	43
Plain	3	855.54	100 × 100	42.5
Plain	4	906.56	101 × 99	42.5
Mono	1	870.66	99 × 100.5	43
Mono	2	866.22	100 × 100	42.5
Mono	3	851.54	100 × 101	43
Mono	4	872.28	100 × 100	43.5
Fibril	1	868.18	99 × 100	43
Fibril	2	873.96	100 × 100	44
Fibril	3	891.82	100 × 101	43.5
Fibril	4	888.04	100 × 100	45

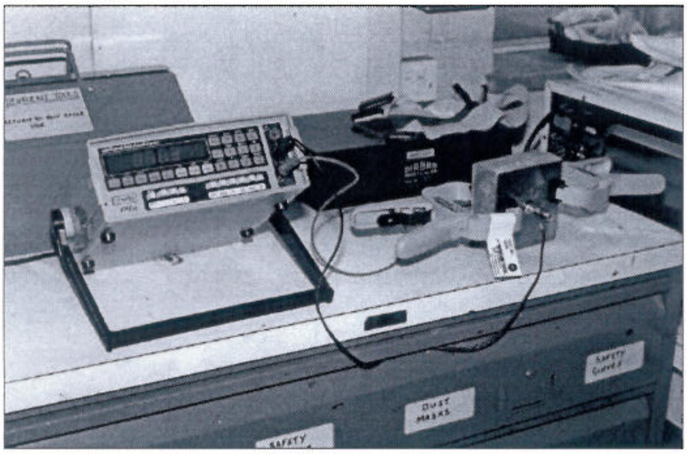
Notes: Plain – cement grout; mono – cement grout with 19 mm long 22 μm monofilament polypropylene fibres; and fibril – 38 mm long fibrillated polypropylene fibres diameter, the assumption made was that dispersion would be reasonably complete.

The sample was tested and the resistivity recorded for 20 per cent moisture content. Twenty per cent of additional water was added to the same sample, 30 min elapsed for full absorption and the sample was tested for resistivity as described earlier. The process was repeated until a series of results was obtained between 0 and 100 per cent moisture content and the results were recorded and findings compared. It was anticipated that the addition of water to the cement samples would provide a corresponding increase in conductivity, according to Mc Carter *et al.* (2001, p. 6) "As the level of saturation of the capillary pores change, there is a corresponding change in the bulk electrical properties of the concrete which can vary over several orders of magnitude".

It was considered that the rehydration of the samples in a single direction, e.g. the base of a tray, will replicate the normal wetting found in concrete structures in a practical field situation. This rehydration is the opposite of that described by Chrisp *et al.* (2002) when curing the cubes, prior to the wetting and drying regime and subsequent electrical measurement testing. The degree of water absorption is the sorptivity multiplied by the square root of time, in addition given the large area compared to the percentage of water to be absorbed, it was considered prudent to use a default figure of 30 min to allow full permeation of the small sample.

The proposed test is similar in composition to that devised by Whitting (1981) and should provide a realistic appraisal and comparison of the potential for flow of ions through various cement composites. Testing apparatus was constructed with 100 mm × 100 mm copper plates soldered into leads, fed into a Thurlby 1905A, Intelligent Digital Multimeter (Plate 1).

Plate 1 Test apparatus for DC resistance



The instrument was checked against a standard resistor and this proved to be exceptionally accurate with no significant errors and produced a voltage of 1.1 DC volts, independently checked on a hand held volt meter. The grout samples were weighed on an electronic balance, measured in 3D and the results were recorded (Plate 2).

The physical properties of the samples are shown in Tables I and II. The electrical properties are shown in Table III.

Analysis of phase 1 of the resistivity testing with a DC current

Problems were encountered in obtaining a good and consistent electrical contact with the grout samples. The gel distribution was a key factor in

Plate 2 Grout sample/electrode detail

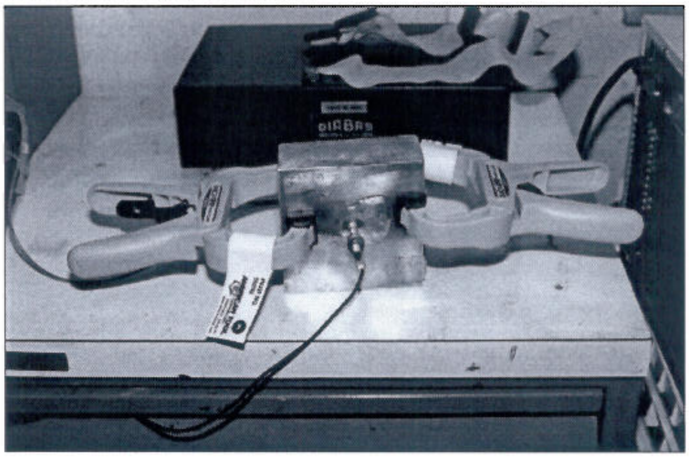


Table II Moisture content of grout samples

Cube type	Cube reference	Wet weight (g)	Dry weight (g)	Moisture content per cent by weight with volume in brackets
Plain	1	902.96	734.98	18.6 (34)
Plain	2	881.06	711.99	19.19 (34)
Plain	3	855.54	680.75	20.43 (35)
Plain	4	906.56	740.94	18.26 (33)
Mono	1	870.66	692.21	20.49 (36)
Mono	2	866.22	688.68	20.49 (36)
Mono	3	851.54	682.32	19.87 (34)
Mono	4	872.28	694.53	20.37 (36)
Fibril	1	868.18	703.84	18.92 (33)
Fibril	2	873.96	708.36	18.95 (33)
Fibril	3	891.82	723.08	18.92 (34)
Fibril	4	888.04	718.17	19.13 (34)

Notes: Plain – cement grout; mono – cement grout with 19 mm long 22 μm monofilament polypropylene fibres; and fibril – 38 mm long fibrillated polypropylene fibres

Table III Electrical properties of samples-resistivity

Cube type	Cube reference	Resistance in ohms × 10^3	Resistance in ohms × 10^3 per cm	Average values per group
Plain	1	0.311	0.071	0.1295
Plain	2	0.435	0.101	–
Plain	3	0.656	0.154	–
Plain	4	0.82	0.192	–
Mono	1	0.684	0.159	0.193
Mono	2	0.778	0.183	–
Mono	3	0.786	0.183	–
Mono	4	1.078	0.247	–
Fibril	1	0.794	0.184	0.187
Fibril	2	0.837	0.190	–
Fibril	3*	0.002	0.0005	–
Fibril	4*	0.028	0.006	–

Notes: *Results with asterisk have been omitted when calculating the average resistance values – due to being outside the standard deviation

affecting the final resistance result. Variations of up to 30 per cent were recorded due to unevenly applied gel. When an inconsistent result occurred the meter was tested against a standard resistance and a series of three further tests were carried out on the sample being tested, varying the amount of contact gel, applied to the surface of the grout. The concept of average reading in this case was an actual reading that was near the median and mode. The length of time the samples were under test varied, however, in some cases an hour elapsed before the readings stabilised, it was considered the grout specimen was not a pure resistor, but was exhibiting a degree of capacitance. This view with regard to capacitance, was also suggested by Lu *et al.* (2000, p. 974).

There is a significant resistance differential between that of plain grout and those with polypropylene fibre additions. The outcome was predicted in an earlier paper by Richardson (2002a), "the dielectric properties of polypropylene fibres in concrete indicate a high resistance to the migration of electrical flow. This being the case, the location of the fibres surrounding the aggregate in the cement paste, will cause a large impedance to the flow of ions thus reducing the water content of concrete, which in turn will affect the performance of polypropylene fibre reinforced concrete to resist the freeze/thaw mechanism", due to reduced water and subsequent ion flow.

Work by Abo El-Enein *et al.* (1995, p. 1615) states, "conductivity can be attributed to changes in the number and/or the mobility of charge carrying ions". This statement gives more justification for carrying out conductivity tests to establish the relative performance of plain and polypropylene enhanced concrete.

Following discussions with Millard (2002), it was considered that the DC voltage to be responsible for the capacitance effect and the tests were repeated with an AC power supply.

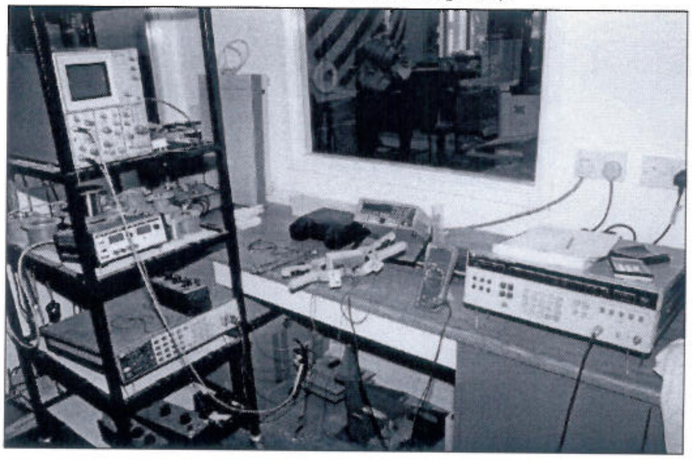
The analysis of the preliminary results shows that monofilament polypropylene fibres have an additional resistance when compared to the plain grout sample of a magnitude of 5 per cent which is corroborated by Millard (2002) as less 1 per cent or alternatively plain grout performs less well when examining its resistivity against monofilament fibres in the order of 3.3 per cent, again slightly less than that found by Millard. Fibrillated polypropylene fibres have an additional resistance when compared to the plain grout sample of a magnitude very similar to that of monofilament fibres or alternatively plain grout performs less well when examining its resistivity against fibrillated fibres in the order of 3.1 per cent.

Flux testing of grout samples using AC single phase electrical supply

The second series of tests were conceived to test flux by measuring the voltage drop across grout samples with and without polypropylene fibre additions using the original samples for this series of tests, for purposes of comparison to the resistance test results. A 3325A Hewlet Packard synthesier/function generator was used to produce a 2 V AC electrical supply, which was monitored by the Thurlby 1905A intelligent digital multimeter. A Fluke 79III True RMS multimeter was used to check capacitance across the sample. The output plate was monitored, by a Hewlet Packard 3456A Digital Voltmeter, and the process was monitored using a 7623A oscilloscope (Plate 3).

Trial tests were carried out using a variety of materials, from plastic sheet to air, to test capacitance and to ensure that the calibration of the equipment was satisfactory. Millard's (2002)

Plate 3 Test apparatus for AC measurement of voltage drop



recommendations on testing equipment is as follows, "If you use a signal generator to input a sine wave current (or voltage) at anywhere around 10-40 Hz and measure the resulting voltage (or current) then you should get a measurement free of polarisation effects". This recommendation is adhered to, in that a 2 V supply was used at 30 Hz. Capacitance was measured across the samples at an average value of 6 μF and the samples were tested within a few minutes of being removed from the holding tank, therefore the samples were at a saturated moisture content level.

The electrical properties per saturated sample are shown in Table IV.

Average voltage drop values per group are shown in Table V.

Monofilament fibres have an increased resistance with regard to voltage drop in the order of 56 per cent compared to plain grout, which would indicate that they are very effective at prevention of ion flow. Fibrillated fibres showed an increased resistance to flow in the order of 8 per cent, however, surface contact problems may be responsible for this reading and result. This gives an indication as to the dielectric properties of the cement grout with polypropylene fibre additions. As polypropylene has a dielectrical constant of 10^{-17} per cm, it was predicted (Richardson, 2002a) that it would have a significant effect on the ion flow through cement grouts and these results appear to lend credence towards that theory.

Analysis of phase 2 of the flux testing with an AC current

From the voltage testing carried out, it is clear that there is a link between the results, with monofilament polypropylene fibres producing the most significant effect in terms of impedance to electrical flow through the concrete.

Table IV Electrical properties of saturated samples-capacitance

Cube type	Cube ref	Input plate volts	Output plate volts	Volt drop	Sample thickness	Voltage drop per cm
Plain	1	2.095	2.086	0.009	44	0.0021
Plain	2	2.098	2.072	0.026	43	0.0061
Plain	3	2.095	2.083	0.012	42.5	0.0028
Plain	4	2.098	2.077	0.021	42.5	0.0049
Mono	1	2.099	2.056	0.043	43	0.0100
Mono	2	2.101	2.051	0.050	42.5	0.0118
Mono	3	2.101	2.070	0.031	43	0.0072
Mono	4	2.102	2.069	0.033	43.5	0.0076
Fibril	1	2.096	2.087	0.009	43	0.0021
Fibril	2	2.100	2.080	0.020	44	0.0045
Fibril	3	2.100	2.079	0.021	43.5	0.0048
Fibril	4	2.101	2.075	0.026	45	0.0058

Notes: Plain – cement grout; mono – cement grout with 19 mm long 22 μm monofilament polypropylene fibres; and fibril – 38 mm long fibrillated polypropylene fibres

Table V Voltage drop

Sample	Voltage drop (average) per cent	Co-efficient of resistance to flow compared to plain grout
Plain	0.00398 (0.199)	0
Monofilament	0.00915 (0.457)	2.29
Fibrillated	0.00430 (0.215)	1.08

Notes: Plain – cement grout; mono – cement grout with 19 mm long 22 μm monofilament polypropylene fibres; and fibril – 38 mm long fibrillated polypropylene fibres

Flux testing of grout samples using AC single phase electrical supply with variable moisture content

The same apparatus as described earlier was used for AC testing. Samples were taken from the drying oven at 105°C and transferred to a workbench to cool until they reached room temperature, this being 22°C. Calculations were made to establish the exact moisture content of each sample; taken as values in grams and this value was divided by five to establish increments of 20 per cent water additions to each sample.

After measuring the conductivity and resultant voltage drop between the two conducting plates of the oven dry samples, again 20 per cent of water was poured into a tray and allowed to be absorbed. It was found that the time taken for water absorption per sample was 5 min in the first instance to 45 min in the final application, 30 min was the standard time left for the water to disperse, during which time the sample and tray was covered with polythene to prevent evaporation.

The purpose of this phase of testing, was to monitor any observable changes in moisture content allied to the respective change in capacitance and then to analyse the results. Following the first set of values obtained from the readings taken, there was noticeable scatter or possibly a variable resistance from the plate contact, therefore it was considered prudent to repeat the tests with identical grout paste samples and average the findings, which gave a smoother statistical profile.

Test results from incremental water additions to oven dry samples (Table VI).

Examining the average values of voltage drop, there is a 0.4 per cent greater capacitance for monofilament fibres, thus indicating the lower potential for ion flow in cement grouts with

Table VI Rehydrated sample capacitance values

Fibre type depth mm and m.c.	Input plate (V)	Output plate (V)	Voltage drop	Voltage drop per cm	Average voltage drop (cm)
Plain 44	–	–	–	–	0.0371
0 m.c.	2.080	1.710	0.370	0.0841	–
20	2.083	1.824	0.259	0.0589	–
40	2.080	1.905	0.175	0.0398	–
60	2.082	1.951	0.131	0.0298	–
80	2.083	2.047	0.036	0.0082	–
100	2.095	2.086	0.009	0.002	–
Mono 43	–	–	–	–	0.0386
0 m.c.	2.082	1.694	0.388	0.0902	–
20	2.080	1.853	0.227	0.0527	–
40	2.082	1.914	0.168	0.0391	–
60	2.081	1.971	0.110	0.0256	–
80	2.081	2.021	0.060	0.0139	–
100	2.099	2.056	0.043	0.0100	–
Fibril 43.5	–	–	–	–	0.0381
0 m.c.	2.081	1.699	0.382	0.0878	–
20	2.080	1.859	0.221	0.0508	–
40	2.082	1.920	0.162	0.0372	–
60	2.083	1.935	0.148	0.0340	–
80	2.082	2.010	0.072	0.0166	–
100	2.096	2.087	0.009	0.0021	–

Notes: Plain – cement grout; mono – cement grout with 19 mm long 22 μm monofilament polypropylene fibres; and fibril – 38 mm long fibrillated polypropylene fibres

monofilament polypropylene fibres. These results are particularly significant when the overall moisture content is considered, as the monofilament samples had the highest moisture content (Figure 1).

From the empirical observations, it was apparent that the monofilament samples absorbed the water quickly as bubbles could be seen rising freely through the water. The given samples were pure grout, no cracking was visible with the naked eye. As earlier discussed it is the ionically charged water in the pores and capillaries that conduct electrical flow, then the results as obtained must be from another factor in the equation other than ionically conducting fluid. This leads the author to consider the effects of the polypropylene fibres as predicted (Richardson, 2002a) it does

Figure 1 Comparative capacitance shown as a voltage drop in relation to moisture content

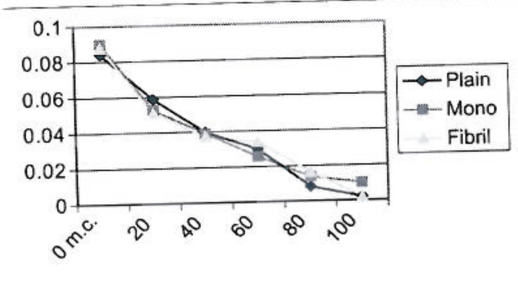
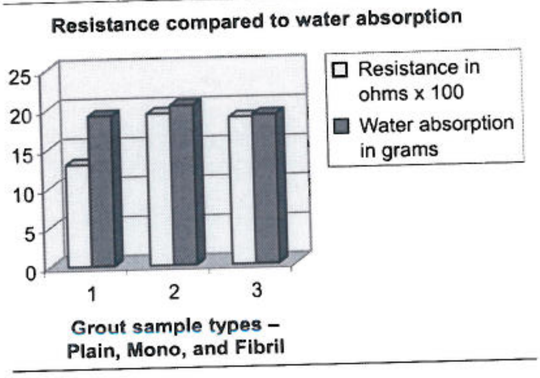


Figure 2 Grout electrical resistance compared to water content



affect the ion flow in concrete and cement grouts (Figure 2).

Summary of test results

The resistivity tests show a 5 per cent additional resistance when monofilament polypropylene fibres are used in cement grout. Impedance shows a much greater voltage drop in the region of 50 per cent although the values throughout are very small. The additional 5 per cent resistance is not significant *per se*, however when considered co-currently with enhanced properties as discussed in the introduction section, the addition of monofilament polypropylene fibres in concrete will provide enhanced qualities with regard to superior durability. A particular significance was found to be the water absorption in cement paste when compared with resistivity measurements taken. These results highlighted the efficacious nature of monofilament fibres, when used in OPC grout or OPC concrete, as the cement binder is mainly responsible for the transmission of water through the concrete matrix.

What was not accurately determined, was the mechanism by which grout samples with polypropylene fibres achieved their superior resistance to the flow of electrons. To a small degree, the resistance and impedance measurements taken may be an abstract way of measuring absorption; and in this regard it must be viewed alongside the absorption results, although pure cement grout exhibits very different absorption qualities when compared to the same OPC used in concrete. The question in need of being addressed, is, "Is it the effect of the polypropylene fibre reducing the conductivity of the sample, or is it the polypropylene fibres affecting the absorption, which in turn is affecting the degree of ionically conducting fluid available to measure the results; thus affecting the degree of resistance being measured".

The degree of moisture retained in the samples has helped achieve clarification of the results. The moisture content is highest with regard to the monofilament fibre samples and lowest with the fibrillated samples. These results are not consistent with the water absorption results normally achieved, (Richardson, 2003c) where monofilament fibres produced the lowest absorption factor in the concrete matrix. If the moisture content of the monofilament fibre samples was the highest, then it would be expected that these samples would have the lowest resistivity as they have the highest moisture content. If the resistivity continues to be the lowest, then it must be attributable to a factor, other than the ionically conducting free water in the grout samples.

The early premise offered by Mc Carter *et al.* (2001) that moisture movement takes place in the cement paste and the aggregates do not appear to be borne out, in that, the overall moisture content for the paste is approximately on an average, six to seven times higher than the BS test (1881: Part 122) for water absorption within concrete.

There appears to be a justification in examining the cement paste only as this is the most significant transport medium within the concrete matrix. The results appear to be conclusive as there is a trend towards a higher resistance to the flow of electrons in cement paste with monofilament polypropylene fibre additions, however, further testing would aid the validity of these results and in vein; Millard of Liverpool University has carried out independent tests. Millard (2002) concludes that monofilament and fibrillated polypropylene fibres in cement grout have similar resistance measurements, which corroborates the early resistance tests, however, Millard shows a slightly smaller change in resistivity compared to the difference shown by the tests at Newcastle University.

To summarise this work, through e-mail correspondence with Millard (2002), relating to the concrete mix types and the factors affecting resistivity, he states, "of the pore-water itself, by the tortuosity of the ionic path and also by the porosity of the concrete", all of which significantly affect the resistivity of the cement grout or concrete. To give an extreme example: imagine a no-fines concrete with a huge porosity. You could partially saturate this mix and measure a high volumetric water content. However, the resistivity could still be high because there is an inadequate continuous ionic path from one location to another.

It has been shown that the addition of monofilament polypropylene fibres in concrete reduces the overall conductivity of the cement grout. This work was corroborated by Millard in a private communication (2002) and was thought to be insignificant in itself. However, when considered alongside the ability of monofilament polypropylene fibres to reduce water absorption and the subsequent ionic fluid available for ion flow as well as other properties, such as micro reinforcement, freeze/thaw resistance, spalling resistance to fire, low bleed and aggregate stability in the plastic state (Richardson, 2002,a,b, 2003a,b,c,d) it is of significance. When these aspects are viewed with regard to the durability equation as shown in Appendix, there is a reasonable case for consideration with regard to the association of using polypropylene fibres in concrete for enhanced durability and lower life cycle costs.

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Appendix. Equation for durability

$$D = \sum f(\mathrm{A} + \mathrm{PR} + \mathrm{FS} + \mathrm{PO} + \mathrm{WR} + \mathrm{FT} + \mathrm{ELS} + \mathrm{IF} + \mathrm{C} + \mathrm{TC}) + (\mathrm{WCR} + \mathrm{MF} + \mathrm{AE} + \mathrm{S} + \mathrm{E})$$

(equation (1) – Durability with polypropylene fibres)

$D =$ Sum of the effects of polypropylene fibres plus the concrete type, set in the environment (Serviceability limit state design will design durability into the structure due to very small crack widths and predetermined stress levels)

where

D	=	Durability,
A	=	absorption qualities (capillary and pore structure),
PR	=	pressure relief (density of polypropylene – density of concrete),
FS	=	flexural strength mainly from the use of fibrillated fibres (bond),
PO	=	pull out values, mainly from fibrillated or crimped/structural fibres (bond between fibre and cement),
WR	=	water retention in plastic state (low bleed),
FT	=	freeze/thaw protection,
ELS	=	early life strength,
IF	=	ion flow mainly from monofilament fibres (impedance/resistivity),
C	=	consistency of mix (aggregate dispersion and fibre dispersion),
TC	=	thermal conductivity (reciprocal of resistance),
WCR	=	water cement ratio,
MF	=	micro filler (pozzolanas),
AE	=	air entrainment (pore size and per cent voids and distribution),
S	=	compressive strength (N/mm^2)
E	=	exposure conditions.

Equation is detailed in Richardson (2003c).